UPCs: the next generation

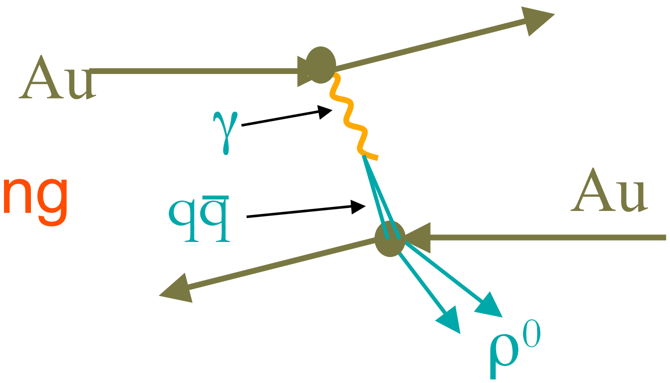
Spencer Klein

- What are UPCs?
  - Photoproduction
  - Two-photon interactions
- Current & near-future at RHIC
- Future Possibilities
  - Roman pots in STAR
  - Possibilities at the LHC
- Conclusions

Caveats

- UPCs are a technique, not a physics topic
- Used to study many physics topics
- Today … the techniques (briefly), then the physics
- Triggers are a key to UPCs. They control what we can do.

UPC Photoproduction



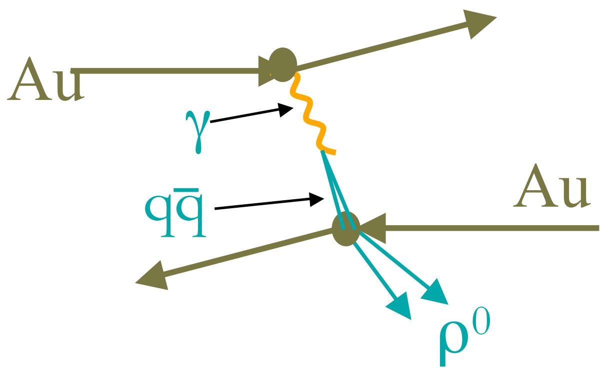
- Nuclei (from protons to gold) carry strong electromagnetic fields
  - Equivalent to a photon beam
    - Photons are quasi-real
- Photons from one nucleus strike the other

	Frame	RHIC	LHC
pp	Lab CM	12 TeV 160 GeV	10 PeV 4 TeV **20X HERA**
AA	Lab CM	600 GeV 35 GeV **~ FNAL**	500 TeV 1 TeV **100X FNAL**

LHC photon energies are far higher than at other accelerators

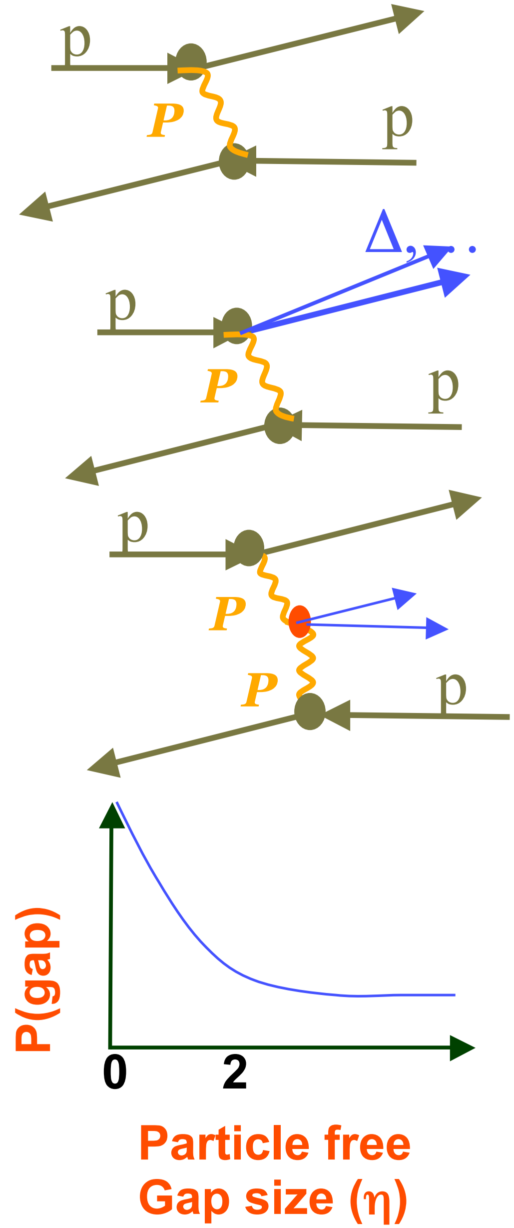
Photoproduction Physics

- Measure gluon structure functions
  - γp/A --> J/ψ, $c\bar{c}$, dijets, etc.
    - $\sigma_{QQ,\ dijets} \sim g(x)$
    - $\sigma_{J/\psi} \sim g^2(x)$
- The strong force without color
  - the “Pomeron”
- Searches for new Physics
- Vector meson spectroscopy
  - Searches for exotica (cf. CEBAF Hall D)
- Tests of quantum mechanics
  - Studies of correlated decays, etc.



The strong force without color

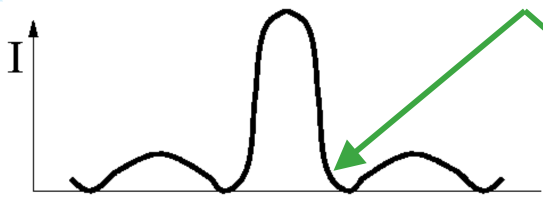
- Many reactions require the strong force without color exchange
  - pp elastic scattering
  - Proton diffractive excitation
  - Vector meson photoproduction
  - High-energy diffraction
    - pp --> pp + 1-2 jets, $b\bar{b}$, $c\bar{c}$, W, etc.
- Isolated final states surrounded by particle-free regions ('rapidity gaps')
  - Color exchange would lead to strings which would fill these gaps
- Rapidity gaps rule out color exchange
  - Would lead to a connecting string --> particles

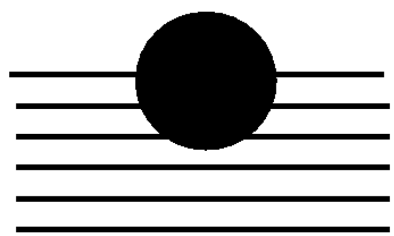


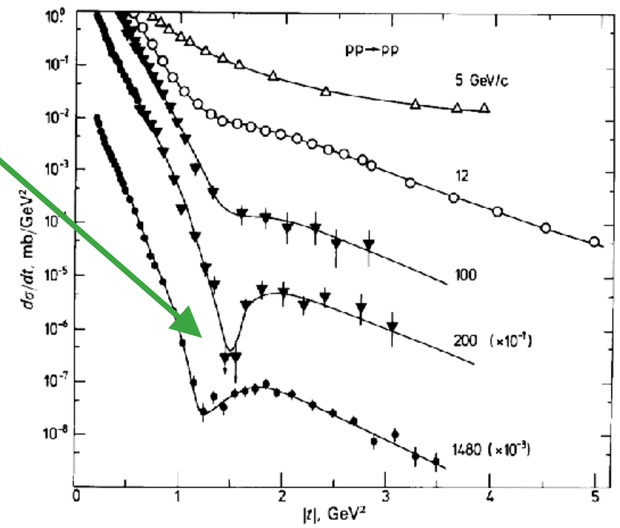
Soft diffraction

pp --> pp

diffractive dip







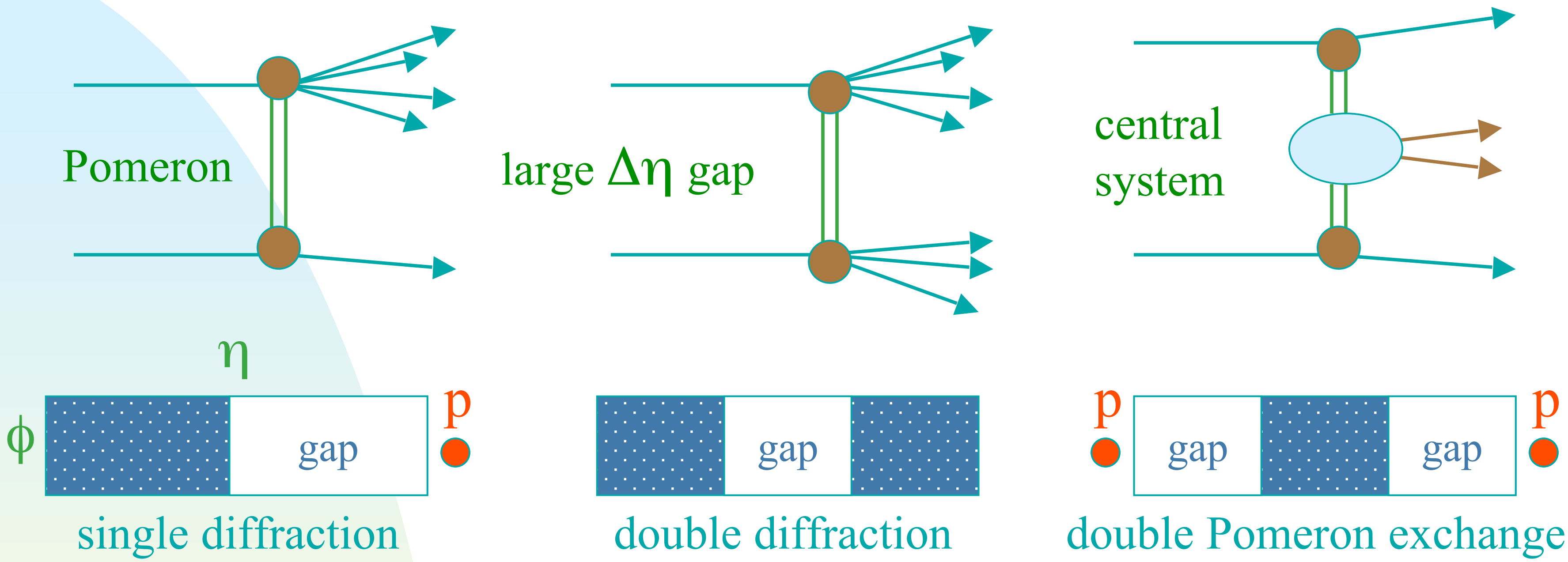
optics → hadron elastic scattering

diffraction: shadow of inelastic interactions (i.e. absorption)

> 20% of σ_{tot} → huge rates

Explains elastic scattering, vector meson photoproduction

What is Diffraction II?



- Diffraction ≡ Rapidity Gap

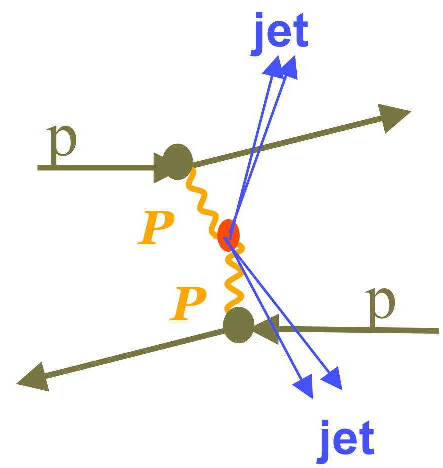
  presumed to be caused by Pomeron exchange

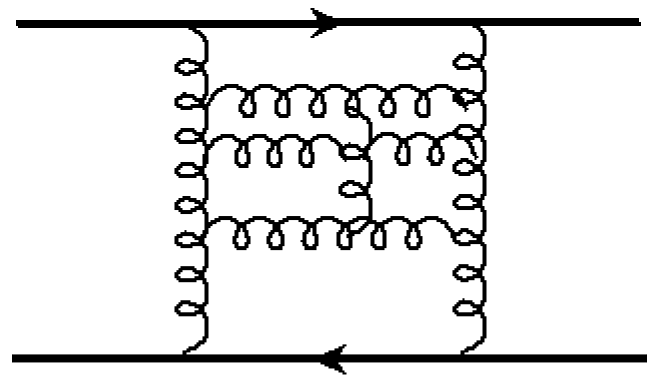
- Pomeron: color-singlet combination of gluons and/or quarks

  with quantum number of the vacuum 0^{++} ?

Diffraction in QCD – the Pomeron

- Soft diffraction cannot explain many phenomena
  - Dijets, other double-Pomeron interactions
- How do hard or soft colorless reactions occur in QCD?
  - 2-gluon states don't have correct behavior
- Requires (at least) infinite 'gluon ladders'
  - vacuum (absorptive) quantum #s $J^{PC}=0^{++}$
  - Many theoretical techniques:
    - BFKL Pomeron, instantons, etc.
      - Lamp-post calculations?
    - A quasi-bound state of gluons?
- RHIC brings 2 elements to the table
  - Heavy ion targets (~ black disks)
  - spin

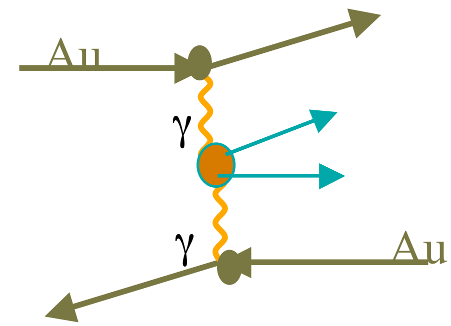




Gluon ladder --> Pomeron

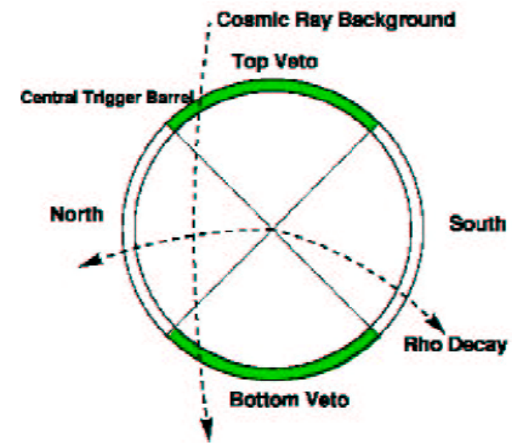
Two-photon interactions

- Largely studied at e^+e^- colliders
  - RHIC luminosity is not competitive with B factories
    - Stress aspects unique to hadron colliders
      - Production of antihydrogen (at Tevatron)
      - Strong field QED ($Z\alpha \sim 0.6$)
      - Pair production with capture
  - LHC reaches higher energies –
    - competitive at W > 10 GeV
- Production of e^+e^- pairs
  - $Z\alpha \sim 0.6$ – Find limits of perturbative QED
- W^+W^- (LHC)
  - Tests of vector boson coupling
- Searches for new physics (LHC)
  - Higgs, magnetic monopoles, extra dimensions, etc.

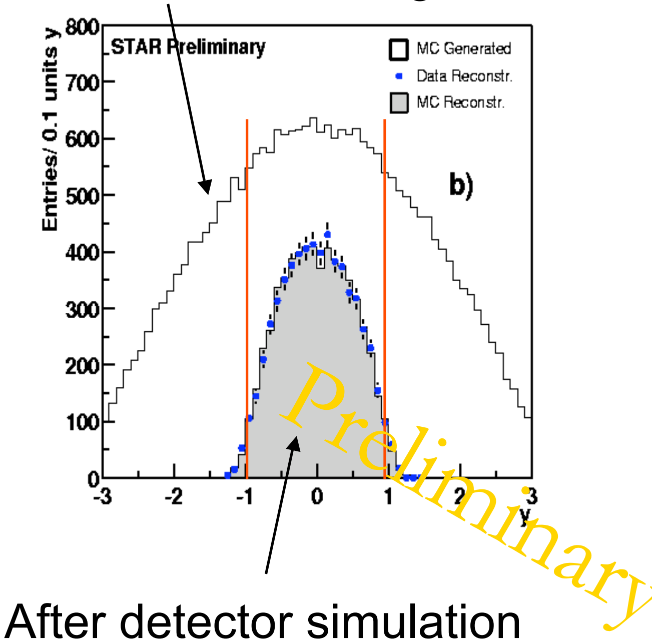


What has STAR learned?

- Much work to develop triggers, algorithms
- The soft Pomeron model describes ρ^0 photoproduction with nuclei
  - The ideas behind UPCs work
- e^+e^- pair production is well described by lowest order QED even for b < ~ 30 fm
  - Moderately surprising to me
  - Limited statistics so far
- Impact parameter tagging
  - Selecting events with mutual Coulomb selects b< ~ 30 fm
    - Ultra-high field region



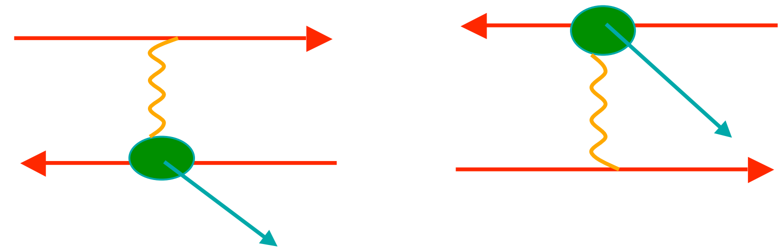
Soft Pomeron, no-shadowing, XnXn

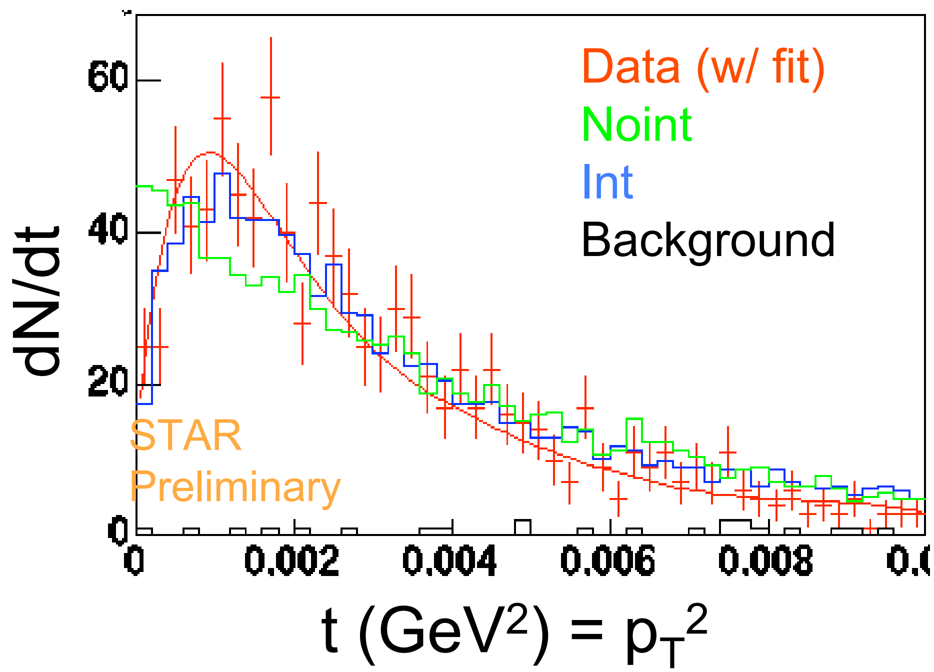


After detector simulation

Interference

- 2 indistinguishable possibilities
  - Interference!!
- 2-source interferometer
  - separation b
- ρ is $J^{PC} = 1^{--}$
- Amplitudes have opposite signs
- $\sigma \sim |A_1 - A_2 e^{ip\cdot b}|^2$
  - At pbar p colliders, interference has opposite sign
- b is unknown
  - For $p_T \ll 1/\langle b \rangle$
    - destructive interference
- Example of Einstein-Podolsky-Rosen paradox



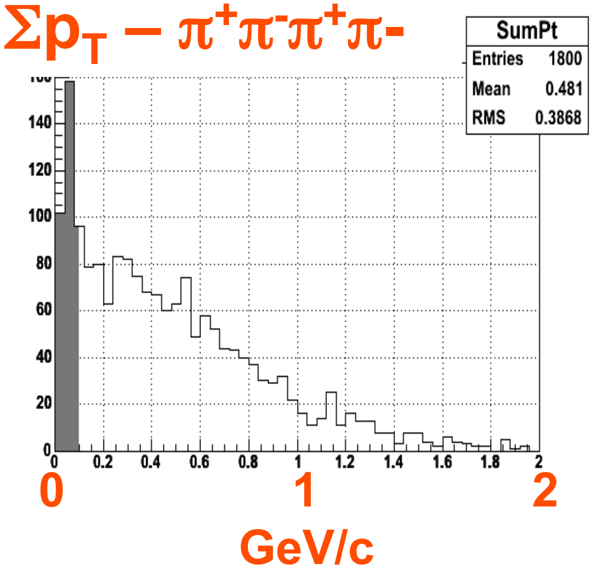


$\rho^0 \longrightarrow \pi^+\pi^-$

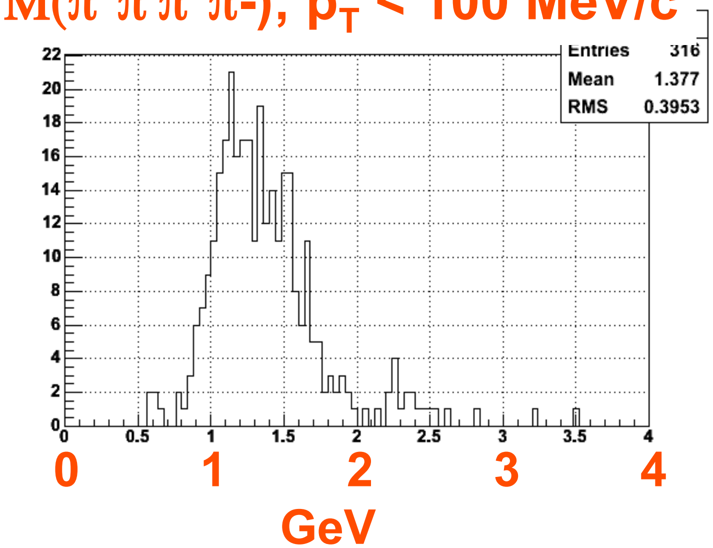
Newer RHIC results

- ρ^{*0} spectroscopy (STAR)
  - $\pi\pi\pi\pi$ final states
  - Is the ρ^{*0} (1450/1700) one state or two?
- ρ^0 photoproduction in dA (STAR)
- Φ --> $K_S K_L$ (STAR)
- σ_{tot}(dA) using γd--> pn (PHENIX)
  - Deuteron photodissociation is used as a 'standard candle' to measure luminosity
- Higher mass $\gamma\gamma$ --> e^+e^- (PHENIX)

Σp_T – $\pi^+\pi^-\pi^+\pi$-



M($\pi^+\pi^-\pi^+\pi$-); p_T < 100 MeV/c

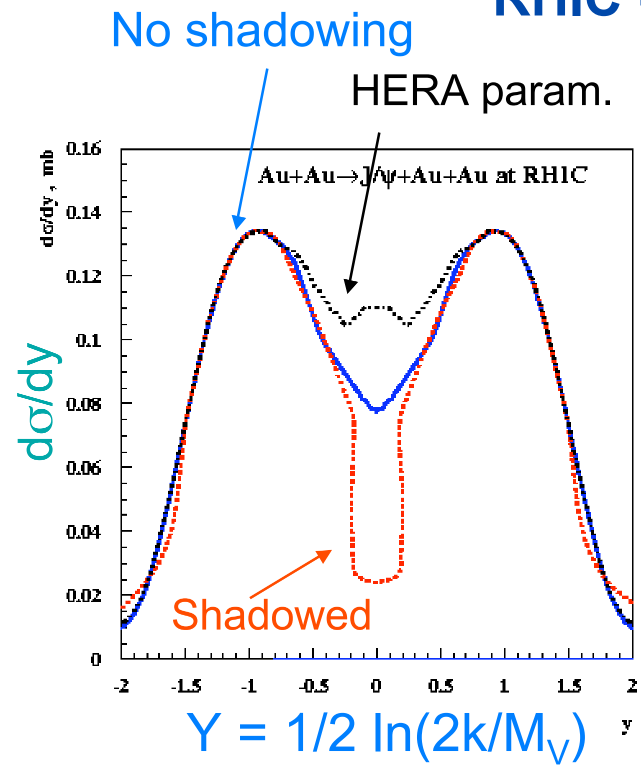


B. K. Kim, Pusan U.

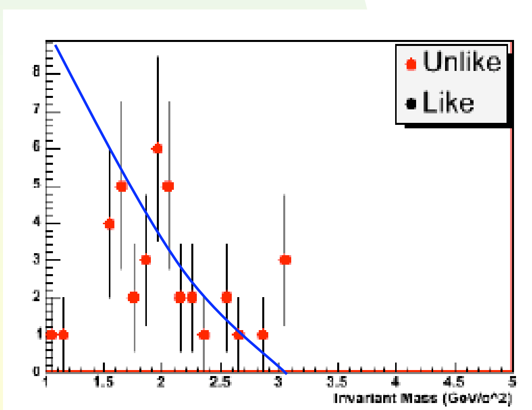
J/y photoproduction

- Measurement of gluon shadowing in nuclei at $Q^2 \sim m_c^2$
  - Test of colored glass condensate
  - N.b. Pomeron ≠ 2 gluons, but…
- CDF, STAR, PHENIX, have seen hints of signal

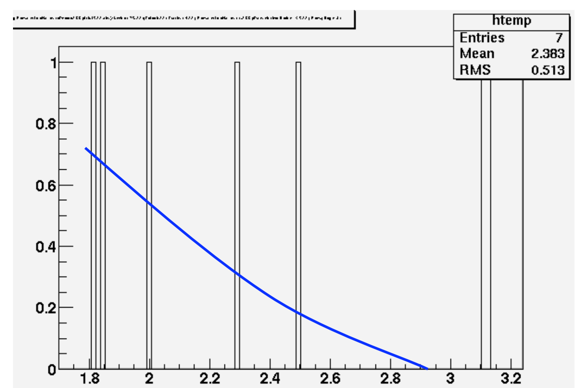
RHIC - Au



Leading Twist Calculation
Frankfurt, Strikman & Zhalov, 2001



AuAu --> Au*Au J/Ψ––> ee ?
PHENIX preliminary (DNP 2004)



AuAu --> Au*Au J/Ψ––> ll ?
STAR 2002 data

RHIC: the next 3-5 years

- High statistics study of J/ψ, ψ' production
  - Accurate measurement of gluon shadowing
- Photoproduction of open charm
  - measure of gluon shadowing
    - Different systematics
    - wider x, Q^2 range
  - Probably requires vertex detector
- ρ^*, ϕ^*, ω^* meson spectroscopy
  - Limits on exotica, Odderons, etc.
- Precision measurement of hadronic radius of gold
- Measurement of e^+e^- production with capture
  - Dedicated experiment/accelerator instrumentation
  - Limits LHC luminosity with heavy ions
- Higher statistics study of e^+e^- pairs?

Photoproduction at the LHC

- J/Ψ, Ψ', Υ to measure gluon shadowing over a wider x range
  - High rates: 780 Hz for J/ψ with lead!
  - ALICE, CMS can trigger on easily
- Open charm/bottom photoproduction
  - Gluon distributions at different x, Q^2
  - Trigger on high p_T lepton
- Photoproduction of top (in pp or light ions)
  - Direct measurement of top charge
- Searches for new physics
- Triggers complicate many possible lower p_T measurements

Two-photon interactions at the LHC

- Searches for new Physics
  - $\gamma\gamma$ --> Higgs – bb
  - $\gamma\gamma$ --> Magnetic monopole
    - Real or virtual
  - Extra dimensions
    - $\sigma(\gamma\gamma$ --> Graviton) depends on $N_{dimension}$
      - Signature is missing energy – how to detect?
  - $\gamma\gamma$ --> pair of sparticles
- Except for extra dimensions, rates for these processes are low
  - Probably not discovery channels
  - Important for determining “what is it?”

Quantum Correlations

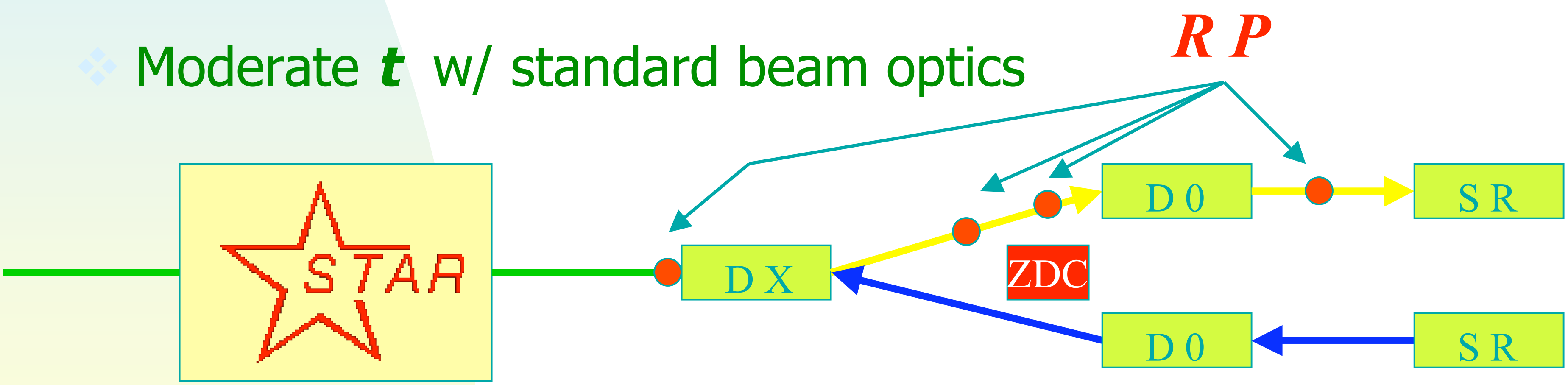
- $P(\rho^0, b=2R) \sim 1.5\%$ at RHIC ($\sim 3\%$ at the LHC)
  - $P(\rho^0\rho^0, b=2R) \sim 0.01\%$
    - 10^6 $\rho^0\rho^0$/year
- $\rho^0\rho^0$ pairs have small Δp & p_T
- Production volume is very small – the two nuclei
  - Superradiant production
    - Bose-enhanced production at small Δp
    - Mini ρ laser
  - ρ^0 will often decay while there is significant overlap
    - Study correlated decays
- Study quantum optics with vector mesons
  - Short-life makes the system unique

pp diffraction at RHIC

- Pomeron-Pomeron interactions dominate
  - Pomerons have a large gluon content
    - Glue-glue collisions
- First high-energy study of diffraction with spin
  - Measure spin structure of Pomeron
    - Pomeron distributions
      - By analogy with parton distributions

Roman Pot Setup with STAR

- Roman Pots ≡ Forward Proton Spectrometers
- Fully reconstruct the event kinematics & trigger on very forward protons
- Low impact on STAR detector
- Moderate ***t*** w/ standard beam optics



- can also be a luminosity monitor

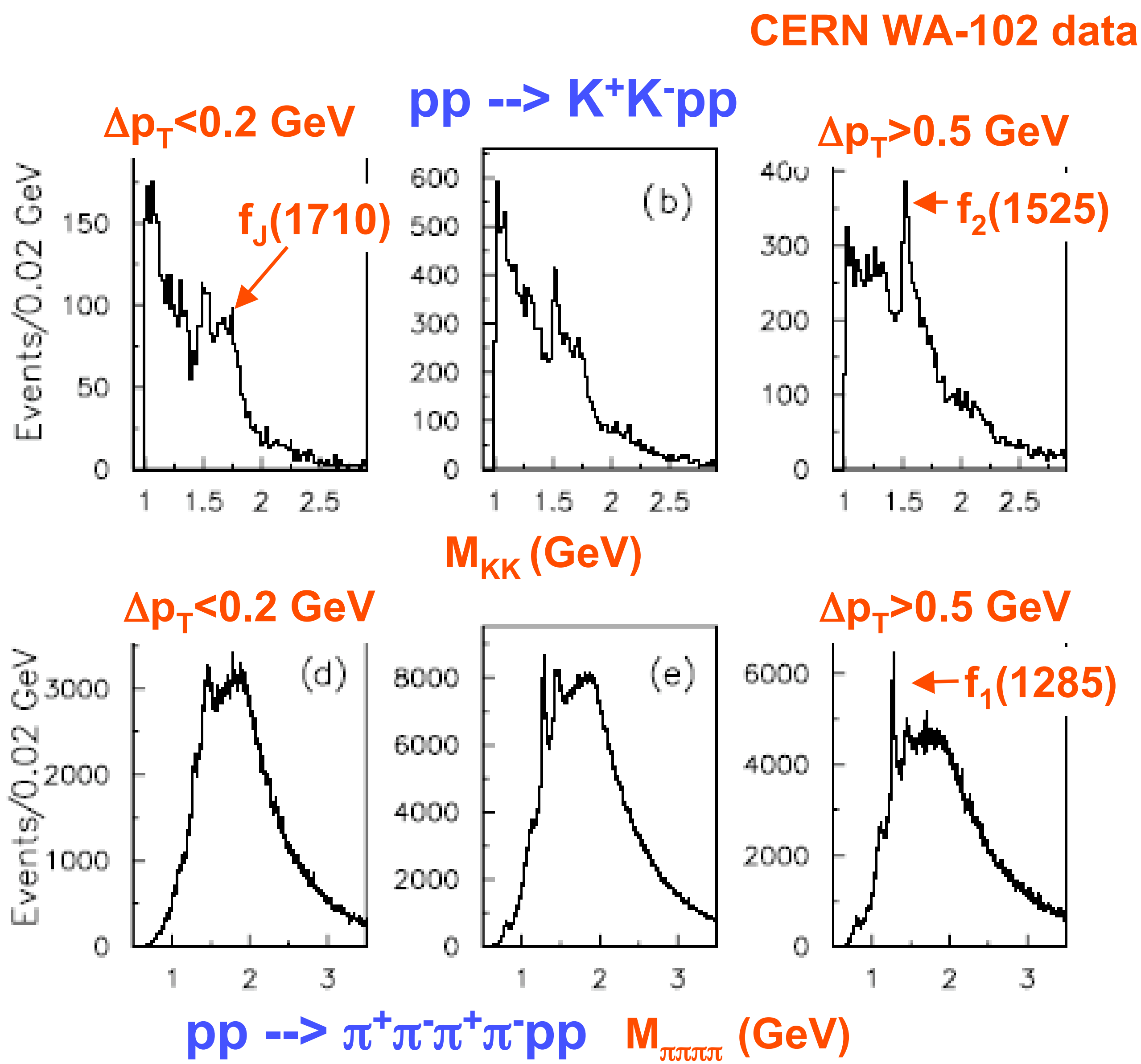
  multiplicity counter out to $|\eta| = 6.5$

  very forward veto

From S. Bravar

Glueballs (& other exotica) in pp

- Δp_T filter separates qq from exotic states
  - Δp_T small for exotica
- Statistics clear
- Mechanism unknown



Glueballs/exotica @ RHIC

- Higher energy
  - No meson exchange contributions
    - Clearer interpretation
- More running --> much higher statistics
  - 100X higher seems attainable.
- Polarized beams
  - Study effect of spin

Hard Diffraction at RHIC

- Study effect of polarization
  - Measure polarized Pomeron distribution functions

Roman Pot Detectors

For these kinematics, probably doesn’t need to be inside beampipe

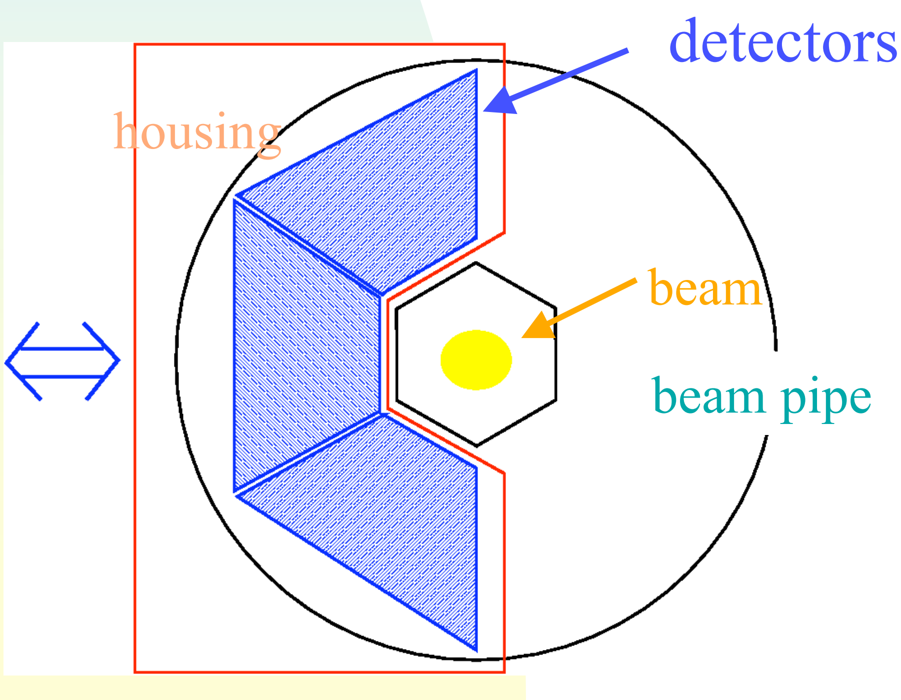
Many possible designs
- scintillator strips
- scintillating fibers
- silicon strips

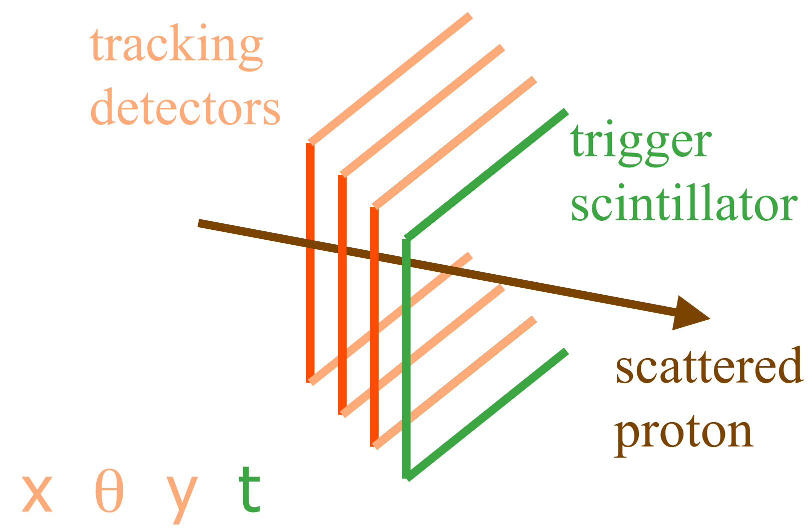
Full azimuthal coverage is desirable
- Complicated by accelerator beam spot shape

hexagonal or rectangular

horizontal & vertical segmentation (or η & φ)

~ 200 μ resolution





Interest

- Considerable interest in Roman pots
  - Sandro Bravar (BNL)
  - Suh-Urk-Chung (BNL) + Pusan group
  - Karsten Eggert (CERN)
    - Testing ground for TOTEM technology
  - Wlodek Guryn (BNL)
    - Move pp2pp Roman pots to STAR
- “Donated” technology may not be optimal
- No critical mass yet
- Cost $200K --> $1M, depending on technology
  - Attractive size in todays budget environment

Roman pots at the LHC

- The TOTEM collaboration is installing Roman pots around CMS
  - Will study pp elastic scattering and inelastic diffraction
  - Can use CMS to study hard diffraction
- ALICE + Roman pots would be an excellent place to study soft diffraction
  - Including charm physics
- Lots of room for new groups

Conclusions

- UPC techniques probe a variety of physics
  - Gluon distributions in protons and nuclei
  - Vector meson spectroscopy
  - Tests of perturbative e^+e^- pair production
  - Studies of quantum-mediated decays
- RHIC still has a lot to contribute
- At the LHC, UPCs can probe gluon distributions at very low x and study some types of new physics.
- With Roman pots, STAR could contribute greatly to our knowledge of exotic mesons
  - The combinations of doubly-diffractive production and polarized beams is unique
  - A rather small investment (mostly manpower) is needed
    - Well suited to the current DOE budget environment.

Backups

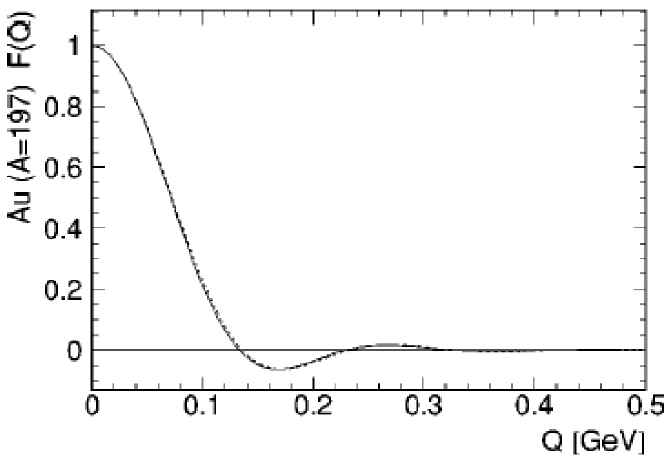
Unique Features of Ultra-peripheral collisions

- Very strong electromagnetic fields
  - γ --> e^+e^- and γ --> $q\bar{q}$
  - Multiple production
- Unique Geometry
  - 2-source interferometer
- Nuclear Environment
  - Particle Production with capture
    - Large σ for e^-

ρ^0 p_T spectrum in UPCs

- Scattering (Pomeron) p_T
  - Modified nucleon form factor
    - Glauber calculation for absorption
    - position-dependent photon flux
- Photon p_T
  - Weizsacker-Williams + form factor
- Add components in quadrature
- w/o interference dN/dt ~ exp(-bt)
  - b = x * R_A^2
    - STAR simulations
    - Woods-Saxon + Glauber calculation
      - (H. Alvensleben *et al.*, 1970)
  - Modifications change x
- Interference
  - Only cause for dN/dt -->0 at small t

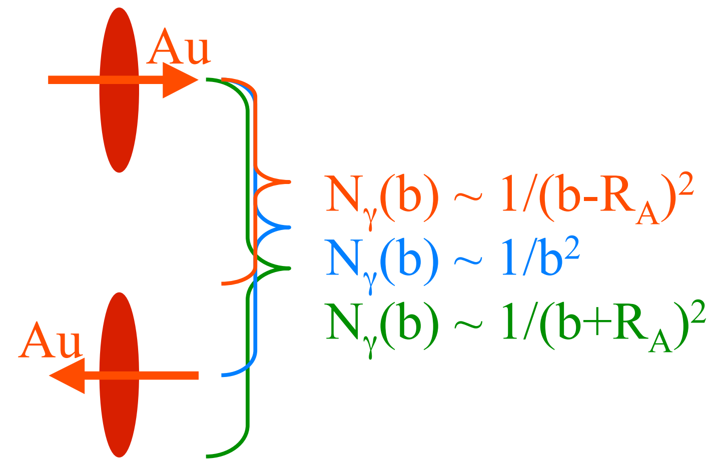
$$t = p_T^2 + t_{\min} \approx p_T^2$$



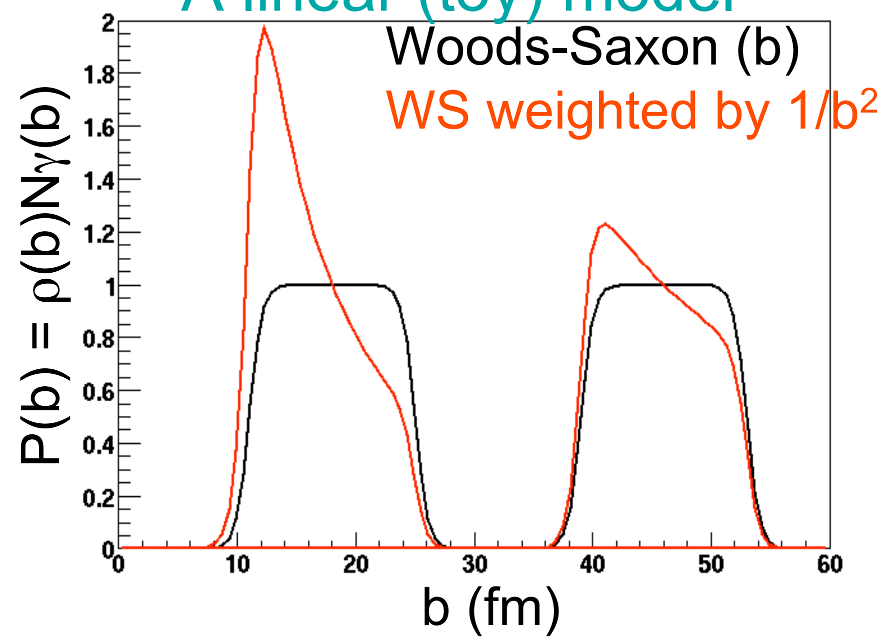
Woods-Saxon Form Factor

Apparent Source Size

- photon flux ~ $1/b^2$
- $P(b) \sim N_\gamma(b)\rho(b)$
- For b ~ few R_A, production is asymmetric
  - Smaller apparent size
  - Small change in σ(tot)
- $\langle b \rangle \sim 3 R_A$ for minimum bias data
- F(t) is Fourier transform of production density
  - Parameter b ~ $(\text{diameter})^2$
- Affects the interference pattern
  - Impact parameter $b_{eff} < b_{geom}$
  - Neglected here

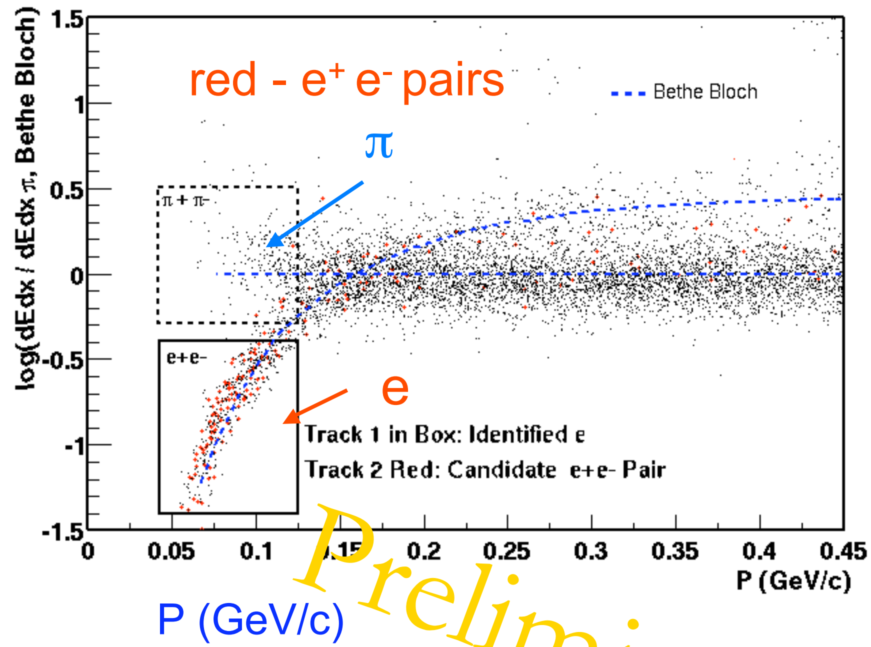


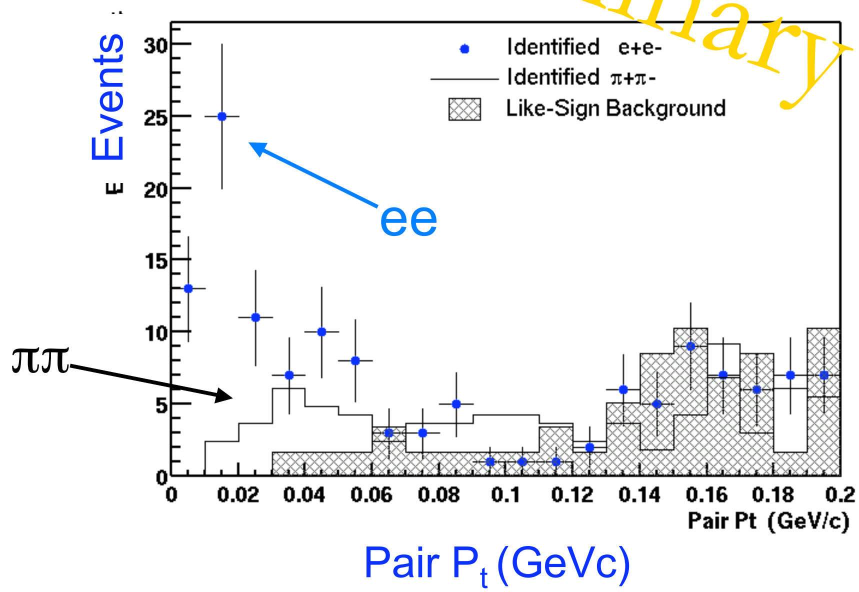
A linear (toy) model



γγ --> e^+e^-

- 'Minimum bias trigger
  - 200 GeV
  - B=0.25T
  - small fraction of data
- Select electrons by dE/dx
  - in region p< 140 MeV/c
- Select identified pairs
- p_T peaked at 1/<b>
  - Different from photoproduced ππ

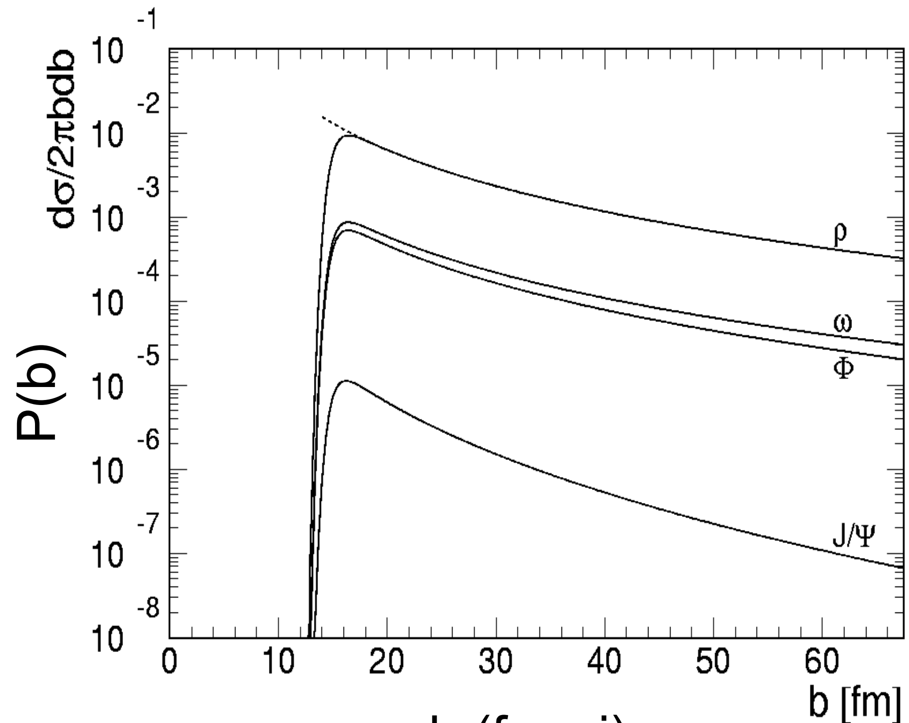




Multiple meson production

- $P(\rho^0) \sim 1\%$ at $b=2R_A$
- w/ Poisson distribution
  - $P(\rho^0\rho^0) \sim (1\%)^2/2$ at b=2RA
  - $\sim 10^6\ \rho^0\rho^0$ /year
- Enhancement (ala HBT) for production from same ion (away from y=0)
  - Vector meson superradiance
    - toward a vector meson laser
  - $\Delta p < h/R_A$
  - Like production coherence
  - Large fraction of pairs
- Stimulated decays?

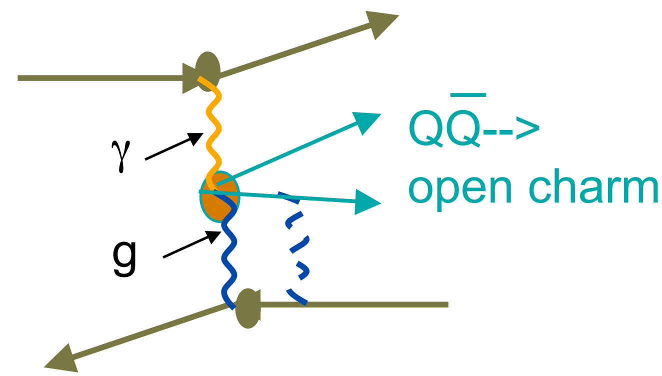
Production with gold at RHIC



b (fermi)

Photoproduction of Open Quarks

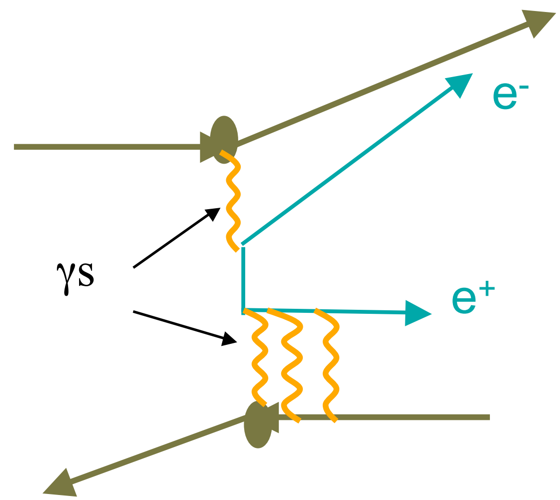
- $\gamma A \rightarrow c\bar{c}X, b\bar{b}X$
- sensitive to gluon structure function.
- Ratio $\sigma(\gamma A)/\sigma(\gamma p)$ --> shadowing
  - removes most QCD uncertainties
- Experimentally feasible
  - high rates
  - known isolation techniques
- Physics backgrounds are $gg \rightarrow c\bar{c}$, $\gamma\gamma \rightarrow c\bar{c}$
  - $\gamma\gamma$ cross section is small
  - gg background appears controllable by requiring a rapidity gap



Production occurs in one ion

Electron Production w/ Capture

- $\gamma\gamma$ -- > e^+e^-
  - Electron is bound to nucleus
  - Probe of atomic physics
  - non-perturbative
  - σ uncertain, ~ 100-200 barns
- Focused $^{+78}$Au beam
- RHIC Rate ~ 10,000 particles/sec
  - beam ~ 40-80 mW
- LHC rate ~ 1M particles/sec
  - beam ~ 10-40 W
  - can quench superconducting magnets
    - limits LHC luminosity w/ Pb
- Could extract as external beam



$Z\alpha$ ~ 0.6; is N_γ > 1?